PREDICTION MODELS OF MICRO-SCALE ABRASION OF THIN COATED SURFACES

A. Ramalho
ICEMS - Departamento de Engenharia Mecânica, Faculdade de Ciências e Tecnologia da Universidade de Coimbra, Pinhal de Marrocos, 3030 Coimbra, Portugal
amilcar.ramalho@dem.uc.pt

***Abstract**. The improvement of the thin films production techniques leads to the availability of a wide range of coatings with high mechanical properties difficult to be reached with monolithic materials. Thin coated surfaces reveal promising results in several applications, specially where high wear resistance is required. However, selecting the best solution for an envisaged application is a difficult task because the tribological performance depends on both coating and substrate properties and also on adhesion between the coating and the substrate. Therefore, the main challenges of the surface engineering includes: suitable procedures to assure enough adhesion between the coating and the substrate; calculation methods to predict the wear and the mechanical behaviour of each coating+substrate arrangement. Ball-cratering micro-scale abrasion technique solve partially this problem once it allows to determine the specific wear rates of coating and substrate by only one set of tests done with the coated surfaces. In this paper, prediction techniques based on the micro-scale abrasion tests, will be presented and discussed. The derived techniques allow the study of ball-on-plane contact and also of crossed-cylinders contact.*

***Keywords**: micro-abrasion, coatings, wear, prediction models.*

1. Introduction

Nowadays, thin coatings are widely used to improve the mechanical properties, particularly wear resistance, of the effective surface of engineering parts. Ball-cratering is now a well-established technique for characterizing thin coated materials. As curved shapes, particularly cylindrical ones, are widely used in mechanical applications, the characterization of coated cylindrical shapes by micro-abrasion could enlarge the application of the technique. A recent paper demonstrates that crossed-cylinder geometry can be used to micro-abrasion testing of cylindrical shapes (A. Ramalho, 2004).

The development of thin hard coatings for tribological applications usually requires a long experimental study to optimize the substrate/film response for the envisaged application. However, recently a model has been developed to predict the abrasion behavior of thin coated surfaces under micro scale contacts that could be used to aid the coating selection (A. Ramalho, 2005).

This paper focuses the development of a complementary model to predict the behavior of cylindrical shaped surfaces. The ability of these models to be applied on coating development will be demonstrated applying the prediction criteria to study the effect of coating thickness and the coating intrinsic specific wear rate.

2. Theoretical concepts

In the crossed cylinder micro-abrasion arrangement a cylindrical coated specimen is tested against a rotating shaft. The crossed cylinder micro-abrasion test is an imposed shape wear test because the wear scar is very small and the contact is fixed relative to the specimen and rotates in relation to the moving shaft. Kassman *et al.* 1991 and Rutherford and Hutchings, 1996 have derived the main theoretical concepts of ball-cratering as a micro-scale abrasive test for coated materials. Ramalho, 2004 extends and updates the principle to be applied to crossed cylinder geometry.

Classical theories of wear present the wear volume (V) proportional to the normal load (L), the sliding distance (S) and the inverse of the hardness (H). The wear coefficient K establishes the proportionality and can be used as a measure of material wear behavior. Both K and H include the material response and can thus be grouped in a parameter, usually called the specific wear rate, k, that can be used instead the wear coefficient K, giving the Eq. (1).

$$V = kLS \tag{1}$$

For bulk materials the specific wear rate can be easily calculated because the normal applied load is transferred totally by the wear scar. However, the study of coated materials raises some specific problems, mainly with respect to thin coatings. The testing of thin coatings usually leads to wear scars through the coating, leading to a bull-eye type pattern, and a mixed contact, coating + substrate, is involved. In general, it is expected that the coating and the substrate exhibit different k values, therefore the wear behavior depends on the response of both the coating and the substrate.

According to Eq. (2), the Archard wear model, as introduced by Kassman *et al.*, 1991, can be applied to the wear of coatings with composite contacts, *i.e.* wear scars that include areas of both substrate and coating materials.

$$SN = \frac{V_s}{k_s} + \frac{V_c}{k_c} \tag{2}$$

In Eq. (2) k_s and k_c are respectively the specific wear rates of the substrate and of the coating. The main differences between the several methods of results analysis to find the values of k_s and k_c are concerned with how Eq. (2) is arranged to explain the specific wear rates as a function of the wear volumes (Kusano, Van Acker and Hutchings, 2004).

The wear scar resulting from a cylindrical coated surface is shown in Fig. 1. For coated specimens, the central part of the area shows the exposed substrate, while the surrounding elliptical annulus corresponds to the wear of the film, Fig. 1 b). It is thus possible, after each test, to measure both the scar corresponding to the surface of the coating, which includes all the wearing material (film + substrate), and therefore will be called the composite scar, and the scar corresponding to the film/substrate interface, which characterizes the substrate wear. Each scar is measured by taking the dimensions of the larger, *a*, and the smaller, *b*, axis of the elliptical wear surface. Considering r_1 and r_2 to be the diameters of the larger and the smaller contact cylinders, respectively, two values of scar depth can be calculated by Eq. (3) and (4).

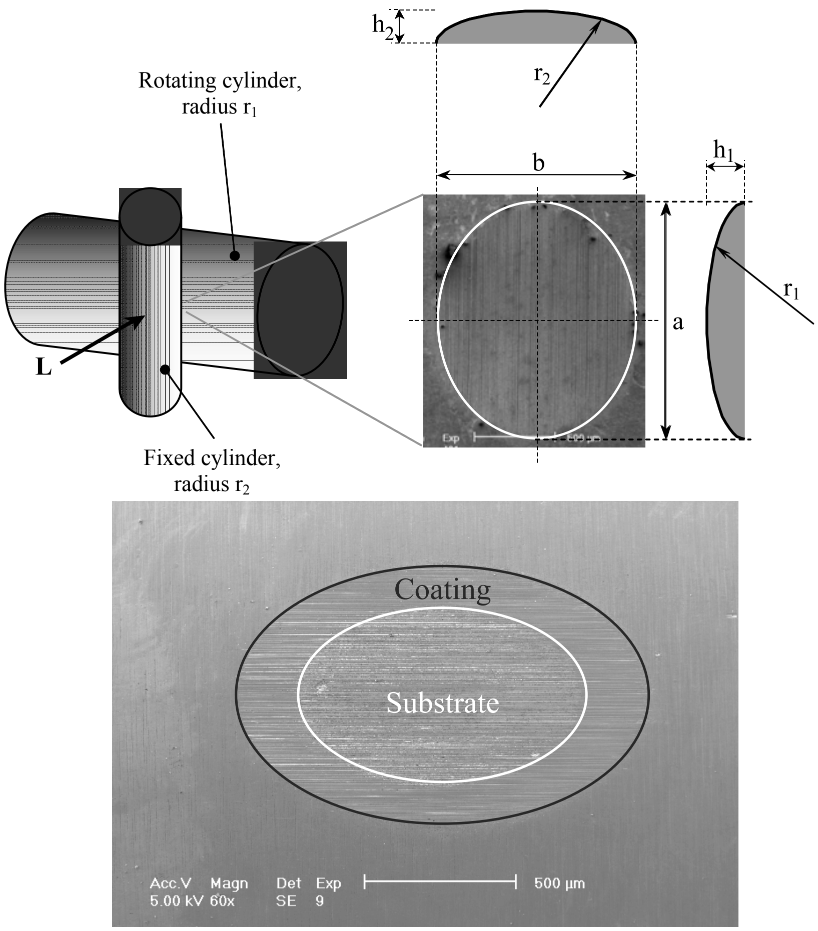


Figure 1. Contact geometry and wear scar on crossed-cylinder micro-scale abrasion.

$$h_1 = r_1 - \sqrt{r_1^2 - \left(\frac{a}{2}\right)^2} \tag{3}$$

$$h_2 = r_2 - \sqrt{r_2^2 - \left(\frac{b}{2}\right)^2} \tag{4}$$

The mean wear depth, h, can be evaluated using the average value of h_1 and h_2; the wear volume can be calculated afterwards using Eq. (5), as derived by Ramalho, 2004.

$$V = h^2 \sqrt{r_1 r_2} \tag{5}$$

The aim of this paper concerns the establishment of a prediction criterion that allows forecasts evolution of wear volumes, and wear depths, for any coating/substrate arrangement under crossed cylinder contact. The prediction criterion is based on the general formulation previously defined assuming that even for perforating tests the development of the scar is always by imposed shape wear and is similar to the procedure previously developed for ball-cratering geometry, Ramalho, 2005.

To apply the prediction model, the thickness of the coating and the specific wear rates k_s and k_c must be known. The prediction model is summaried on flow-chart displayed on Fig. 2, and could be applied step-by-step according to the following procedure:

1- select the maximum depth, h_{max}, of the wear scar and the step Δh to be used on the analysis;
2- the prediction criteria starts with a first total depth of the scar, Δh, that is smaller than the coating thickness, t;
3- assuming that the axis of the elliptical scar are equal to the radius of the contacting cylinders, the values of the scar volume can be calculated. The wear volume of the substrate remains zero while $h<t$;
4- applying Eq. (5), the total wear volume can be achieved, as $h<t$ then $V_c = V_t$ and $V_s = 0$;
5- as the coating specific wear rate has already been found, Eq. (2) allows to calculate the value of *SN*;
6- increasing the scar depth, h, for all practical values of interest, generates new values for V_c and V_t.
7- when $h>t$, the depth h_s of the scar on the substrate can be calculated as $(h-t)$
8- applying Eq. (5) to the substrate and to the total wear depth, the substrate and the total wear volumes, V_s, V_t can be found;
9- the coating wear volume can be achieved subtracting V_s to V_t;
10- V_s and V_c, can be substituted in Eq. (2) allowing to calculate *SN*.

As explained above the model allows the calculation of the relationships between the *SN* values and the wear volumes or between *SN* and the total wear depth. Calculating those values, the graphs with the predictions can be drawn.

3. Applying the prediction model

To verify the ability of the model to forecast the wear in specific applications, Fig. 3 shows the results obtained by applying the model to study the effect of film thickness. Figure 3 a) shows the results obtained applying the model developed in the present paper, whereas Fig. 3 b) displays the results considering the model for ball on plane contact (Ramalho, 2005). The case modeled corresponds to specific wear rates of $2.5\text{x}10^{-13}$ and $5\text{x}10^{-12}$ m^2/N respectively for the coating and for the substrate and the coating thickness was ranged from 1 to 6 µm. The results shows that in spite of the continuous decreasing of wear depth verified when the thickness is increased, the efficiency of the coating is much more evident for values of thickness up to 2.5 µm.

Another case study is showed in Fig. 4 concerning the effect of the specific wear rate of the coating material. The substrate considered has a specific wear rate, k_s, of $5.0\text{x}10^{-12}$ m^2/N, and all the films have a thickness of 4 µm. In order to evaluate the effect of the coating specific wear rate, six different values of the relationship k_c/k_s were studied, namely 2, 1, 0.5, 0.2, 0.1 and 0.05. For both ball-on-plane and crossed-cylinder contacts the increase in the film specific wear rate leads always to a decrease in the wear depth. The obtained results reveal that a reduction on wear depth of almost 4 times could be obtained with the deposition of a 4 µm coating with a specific wear rate 20 times lower than the substrate.

4. Validation of the model

To validate the model a micro-abrasion study was carried out using coated cylindrical specimens, with nominal diameters of 8 mm. The specifications and procedures of the experimental equipment were explained elsewhere (Ramalho, 2004). The rotating specimen used was a DIN Ck45 steel shaft with a diameter of 15 mm. The abrasive medium is a slurry of SiC particles with P2500 grain size, mean size of 8.4 µm, in distilled water, with a concentration of 0.35 g of SiC per cm^3 of water.

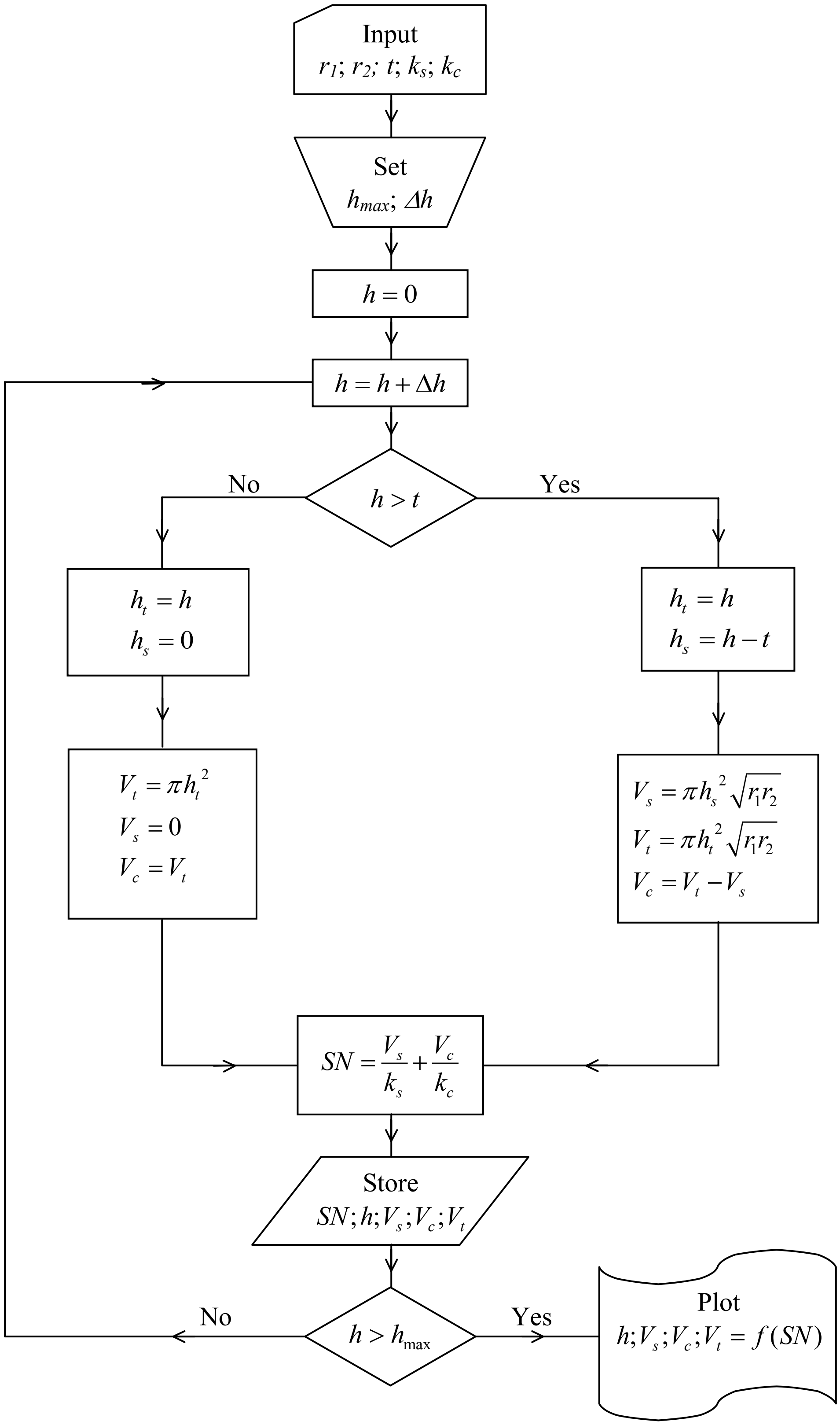
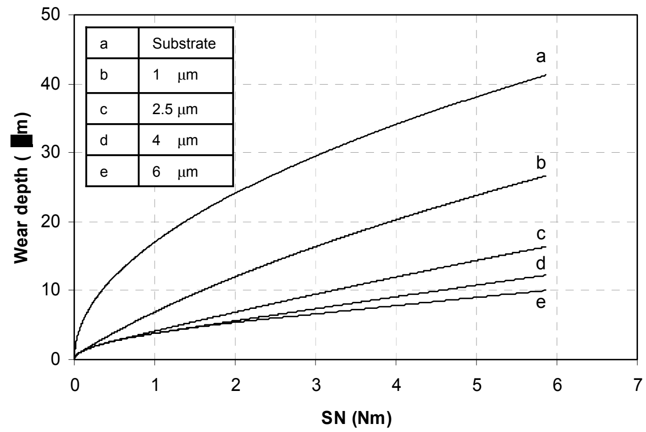


Figure 2. Flowchart of the crossed-cylinder micro-scale abrasion prediction method.

a)



b)

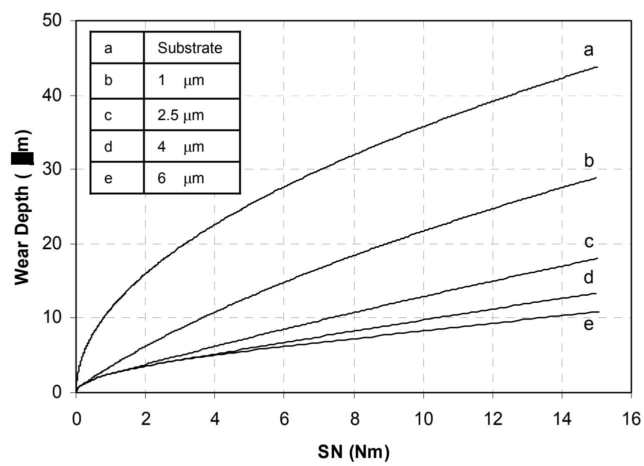


Figure 3. Predicted results for the effect of the coating thickness. a) Crossed-cylinders contact. b) Ball-on-plane contact.

The coated material tested was a pre-treated 38 CrNiMo 4 electroplated with a 15 µm film of hard chromium. The hardness of the tested material was measured both on the core and on the surface obtaining respectively 285 HV1 and 1250 HV0.05. The normal load and the rotational speed were kept constant during the study, with the respective values of 2 N and 100 rpm, which corresponds to a sliding speed of 0.078 m/s.

To characterize the coated specimens a set of tests were carried out keeping constant all the test parameter except the duration. The numbers of rotations considered were: 8, 15, 20, 30, 40, 100, 200, 300, 400 and 500. Three tests were conducted for each condition, and the average value is used in the results.

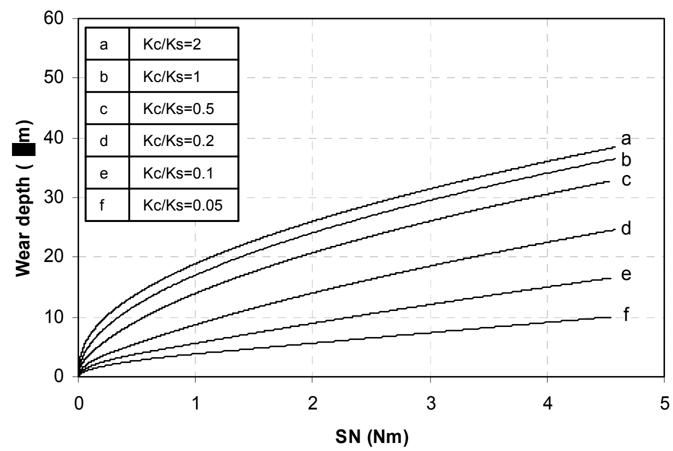
Before and after the test, the samples were been ultrasonically cleaned with acetone to remove all traces of contaminants. A Philips XL30-TMP scanning electron microscope was used to measure the wear scars and to observe the morphology of the wear surfaces.

For the tests above 20 rotations the substrate was reached and Eq. 5 was applied to calculate volume removed from the substrate and also the total volume of removed material. Therefore as described elsewhere (Ramalho, 2004) the values of wear volume could be achieved for the substrate and for the coating, respectively V_s and V_c.

Allsop, 1999, derived a method that allows the separation of the specific wear rates for both substrate and coating from only one set of ball-cratering tests of flat thin-coated surface. At least, the basic principles are the same for both ball-cratering and for crossed-cylinder micro-abrasion, therefore the Allsop procedure will be applied to analyze the results. The Allsop method rearrange the Eq. (2) in order to separate the values of the specific wear rates of the substrate and of the coating, respectively k_s and k_c, obtaining the Eq. (6).

$$\frac{SN}{V_c} = \frac{V_s}{V_s}\frac{1}{k_s} + \frac{1}{k_c} \qquad (6)$$

a)



b)

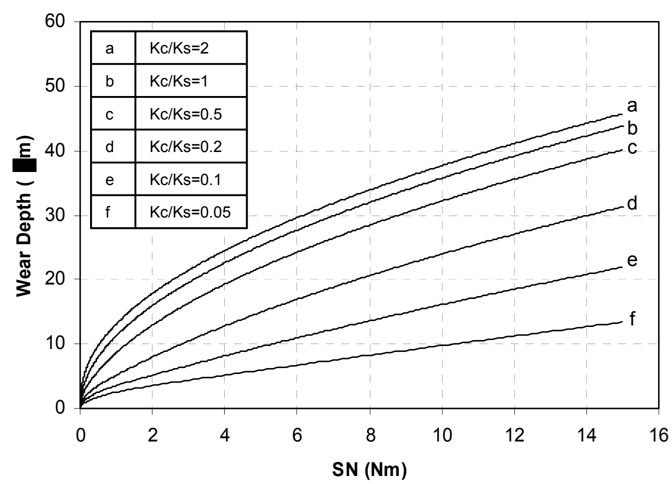


Figure 4. Predicted results for the effect of the coating specific wear rate. a) Crossed-cylinders contact. b) Ball-on-plane contact.

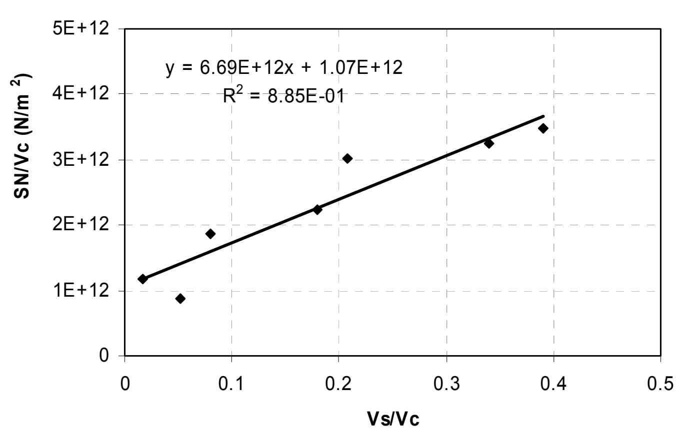


Figure 5. Application of the Allsop method to the separation of ks and kc.

Figure 5 shows the application of Allsop method to analyzing the results and a suitable correlation was obtained. The k_s and k_c values are calculated respectively as the inverse values of the slope and the intercept of the linearization of *SN/Vc* as function of *Vs/Vc*. The results obtained for the tested material are 1.49×10^{-13} and 9.34×10^{-13} m^2/N respectively for k_s and k_c.

a)

b)

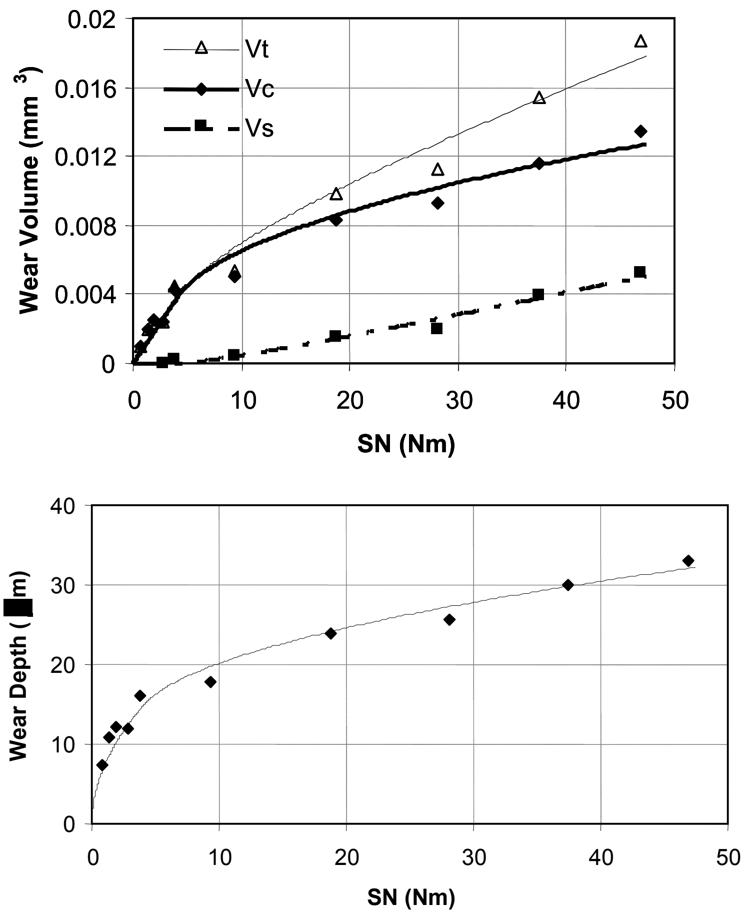


Figure 6. Application of the Allsop method to the separation of k_s and k_c.

To validate the prediction method, the obtained specific wear rates have been used to predict the evolution of the wear volumes and also the wear depth. Figure 6 compares the prediction to the experimental results, the lines represent the forecast values and the points correspond to experimental results. A very good agreement between experimental and predicted values has been achieved both for wear volumes and wear depth. The good correlation between experimental and predicted values justifies the ability of the developed models.

5. Conclusions

The suitability of a prediction model for characterising the wear behaviour of thinly-coated cylindrical surfaces, based on the specific wear rates of the coating and of the substrate, determined in previous tests, has been presented and discussed.

The model developed assumes the imposed shape principle usually considered for this kind of contacts.

The results predicted by the model agree well with experimental results.

The models implemented reveal good suitability to study micro scale contacts. Prediction models could be an helpful tool to apply in the development of new coatings before the phase of testing prototypes.

6. Acknowledgements

This work was done under a project funded by the Portuguese Foundation for Science and Technology (POCTI/33710/EME/2000).

7. References

Allsop D.N., Abrasive wear of bulk materials and hard coatings, PhD thesis, University of Cambridge, 1999.

Kassman A., Jacobson S. , Hedenqvist P. and Olsson M., A new test method for the intrinsic abrasion resistance of thin coatings, Surf. Coat. & Technol., 50 (1991) 75-84.

Kusano Y., Van Acker K. and Hutchings I.M., Methods of data analysis for the micro-scale abrasion test on coated substrates, Surf. Coat. Technol., 183 (2004), 312-327.Ramalho, A. "Micro-abrasive wear test of thin coated cylindrical surfaces", Tribology Letters, Vol.16 Nº1-2 (2004)133-141.

Ramalho A., "Micro-scale abrasive wear of coated surfaces – prediction models". Surf. & Coat. Technol., 197(2005)358-366.

Rutherford K.L. and Hutchings I.M., A micro-abrasive wear test, with particular application to coated systems, Surf. Coat. & Technol., 79 (1996) 231-239.